DISTRIBUTED ACOUSTIC SENSING (DAS) FOR DETECTION OF DEFECTS IN DAMS USING AMBIENT NOISE INTERFEROMETRY

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Summary

The aim of this study was to assess the capabilities of seismic Ambient Noise Interferometry (ANI) with fibre-optic Distributed Acoustic Sensing (DAS) data to monitor earthen dams. A test dam was used to assess the applicability of ANI methodology to small-scale infrastructure with imaging and monitoring of the dam using DAS data. The study highlights anomalous regions in the Älvkarleby Test Dam that may be defects. Problem areas highlighted in this way can be further assessed to determine the need for remediation work. The study demonstrates the potential to combine DAS and ANI techniques to image and monitor infrastructure and landslides at distance from a fibre-optic cable.

Distributed Acoustic Sensing (DAS) for Detection of Defects in Dams using Ambient Noise Interferometry

Introduction

The aim of this study was to assess the capabilities of seismic Ambient Noise Interferometry (ANI) with fibre-optic Distributed Acoustic Sensing (DAS) data to monitor earthen dams. To a limited extent ANI has been applied to dam structures and landslide sites (e.g., Olivier et al., 2019). However, the completeness of the imaging has been constrained by the use of a small number of point sensors, i.e., geophones. With a dense seismic array, as provided by DAS monitoring, it is possible to conduct a detailed survey of dam and landslide sites. The use of DAS for seismic surveys has been validated through the use of traditional seismic processing methods to compare DAS data to data collected using traditional seismic instrumentation (e.g., Miller et al., 2016; Correa et al., 2017). Distributed fibre-optic sensing offers the possibility for densely spaced repeatable measurements over many years with permanently installed cables that can be deployed over large distances.

A test dam was used to assess the applicability of ANI methodology to small-scale infrastructure with imaging and monitoring of the dam using DAS data. The Test Dam at Älvkarleby, Sweden is 20 m-long and 4m-high with defects incorporated during construction. The dam is on a rigid concrete support structure, with a slope of 1%, and is submerged into a drained riverbank. The sidewalls of the dam are slightly angular (12.5%). One fibre-optic cable for DAS measurements is deployed at four levels in the upstream filter and on the core crest of the dam, and a second cable was installed at five levels in the downstream filter (Figure 1). This is a blind test and the aim of the data collection is to determine the location of the in-built defects using continuous monitoring. The defects, representing damage that could eventually result in a dam failure, are:

1. Cavity in the core (wood cube 0.4 m × 0.4 m × 0.4 m).
2. Horizontal permeable zone passing through the core (0.1 m high and 0.5m wide).
3. Vertically loose zone (elongated zone with square cross section with side 0.3 m).
4. Lump of concrete or large stone (cube 0.5 m × 0.5 m × 0.5 m).
5. Permeable horizontal zone at side (0.1 m x 0.1 m).
6. Filter defect on the upstream side.

The locations of the defects have not yet been revealed.

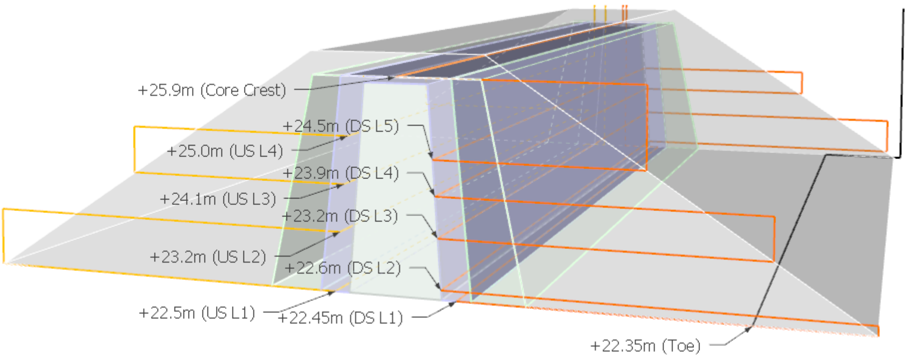


Figure 1 *Cable layout in the Test Dam.*

Silixa iDAS v2 interrogators were used for data collection. A gauge length of 3m was used with a recording frequency of 1kHz and a channel spacing of 0.5m. This provided high-quality data suitable for ambient noise interferometry analysis. The DAS measurements were made during two periods when the reservoir behind the dam was filled and emptied. The measurement periods were:

- Phase 1: 6 April to 29 June 2020 during dam first filling (Johansson et al., 2020).
- Phase 2: 26 August to 11 November 2021 during dam emptying (Johansson et al., 2022).

Monitoring and Imaging Methods

Passive seismic methods make use of the natural or anthropogenic noise and do not require direct human intervention, resulting in cost savings compared to active seismic methods. Data can be recorded on-demand, independent of weather conditions or time of day, and can be performed continuously if required. The recorded signal provides information on the velocity and amplitude of the seismic waves in the dam, which may then be related to material properties.

Given the advantages of passive seismic methods and distributed fibre-optic sensing, the feasibility of using ANI in combination with DAS measurements to image and monitor seismic velocity variations in the dam is tested. We assess the potential for timelapse imaging was using eikonal tomography (Lin et al., 2009; Mordret et al., 2013) and use coda-wave interferometry (Snieder et al., 2002) to measure the relative seismic velocity changes within the dam for the whole monitoring period.

Data recorded on the cable in the crest of the dam is used for the analysis. For imaging, parameters were tuned over 5 day-long stacks of correlations at 4 different water level stages before performing a batch computation of the one-day time lapse tomography. Imaging is performed on all channel pairs sorted in 40 virtual shot gathers (i.e., each channel taken as a virtual source versus all the other channels taken as virtual receivers) and travel-time measurements were made between 10 to 25 Hz. The dispersion measurements were inverted to obtain models of S-wave velocities (Vs) versus depth.

The maximum resolution of the velocity model is larger than the defect size, making imaging on this scale challenging. However, changes in the dam can be identified on a smaller scale and methods were adapted to enable monitoring of the small dam (Mordret et al., 2022). The monitoring application is performed on 35 channel pairs with similar inter-channel distances sampled along the dam every 0.5 m along the crest fibre. Stable results are obtained with a temporal resolution of 30 minutes.

Imaging Results

The S-wave velocity model obtained for the dam is well resolved between 1.5 m and 5.5 m deep (e.g., Figure 2). Velocities in the dam range between 160 to 320 m/s, and below the dam velocities range between 200 and 800 m/s. The velocity anomalies highlight lateral variations in the dam with strong positive and negative velocity variations up to 30% in the dam. There is a strong positive velocity anomaly below the dam around Section 20.

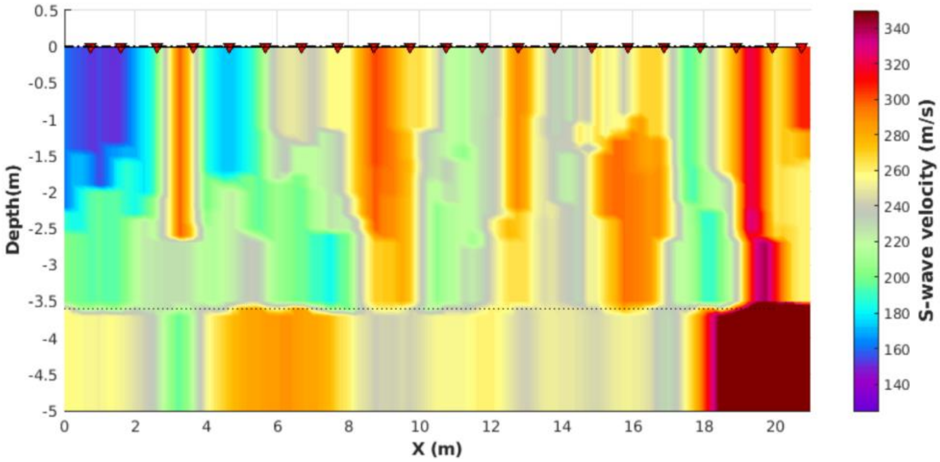
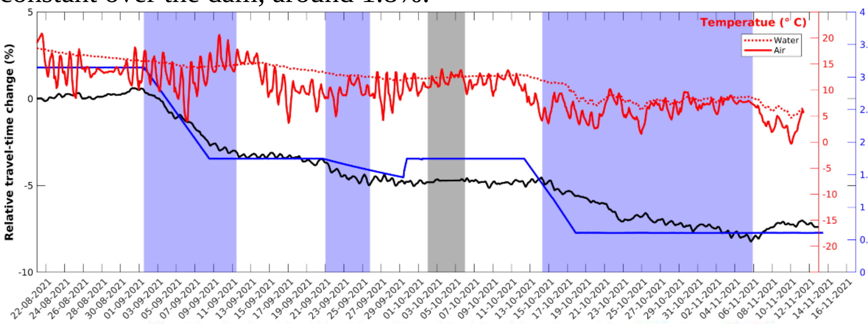


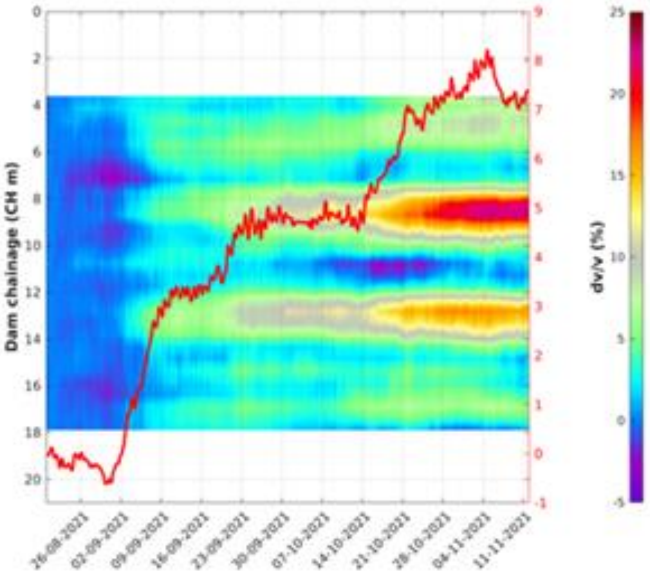
Figure 2 *Vs model obtained from the first phase of analysis.*

Monitoring Results

Daily oscillations in travel times are found during both phases of recording and overall velocity decreases are observed with filling and velocity increases with draining. For example, Figure 3 shows the average travel time variations (black line) together with water temperature (dotted red line), air temperature (red line) and water level measurements (blue line) for the Phase 2 recording. There are three periods of significant travel-time decrease (highlighted in blue), resulting in a cumulative travel-time change of about 8%. The first two periods occur during water drainage. The third period starts a couple of day after drainage restarts and extends over 10 days. The travel-times have consecutive step-like decreases correlated with drainage of the basin. These steps are smaller each time there is a water drainage. Spatial velocity anomalies provide information on the location of defects. Sections of the dam around 9 and 13 m sustained a velocity increase of >20% during draining (Figure 3b). Conversely, some parts of the dam (e.g., Section 11) are not affected by the water level change. The uncertainty on the measurements is constant over the dam, around 1.8%.



a)



b)

Figure 3 *Monitoring results for Phase 2. a) average travel time variations (black line) with water temperature (dotted red line), air temperature (red line) and water level measurements (blue line). b) dv/v measurements along the dam. The red line shows the average dv/v throughout the dam.*

Combined Results

The result from imaging and monitoring based on data collected from the crest cable shows that that the ANI monitoring method enables the detection of small velocity changes, with a very good accuracy. The imaging method is less accurate both in terms of time and velocity, but it provides more detailed spatial information. Thus, the results from both methods combined are used to provide the location of the velocity changes and hence the potential location of the in-built defects. Figure 4 shows the identified most likely locations of defects with shaded areas. The actual locations of the defects are yet to be revealed.

Conclusions

The study demonstrates the potential to combine DAS and ANI techniques to image and monitor earthen dams and other monitoring targets such as dykes or landslides. This provides information at distance from the cable and could be used to highlight damaged or anomalous areas throughout the asset. Using the imaging and monitoring techniques of eikonal tomography and coda-wave interferometry we highlight anomalous regions in the Älvkarleby Test Dam that may be defects. Problem areas highlighted in this way can be further assessed to determine the need for remediation work.

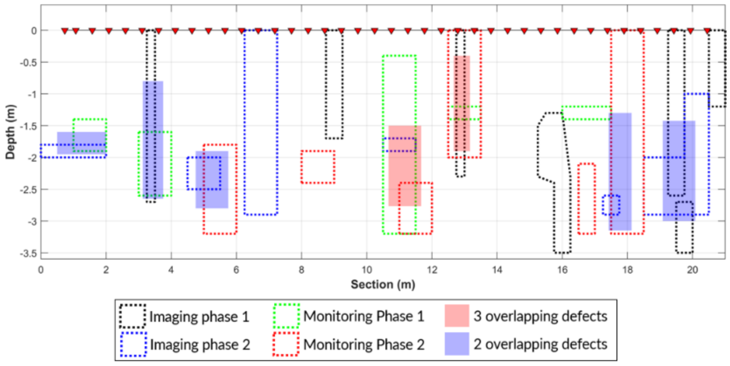


***Figure 4** Defect identification summary. Areas of velocity anomalies identified by both the imaging and monitoring and/or during both monitoring phases (the blue and pink shaded areas).*

Acknowledgements

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